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Multi-objective optimization of die geometry in ingot forging

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Abstract

The soundness of an ingot after hot forging with different V-shaped lower dies is evaluated using finite element simulations. Two different modelling approaches that make use of uncoupled ductile damage and coupled ductile damage based on porous plasticity are employed. It is shown that the two approaches provide somewhat different results. A simple quantification scheme is suggested for ranking the overall performance of the different geometries of the V-shaped lower dies. Results show that a lower die angle in the range 90°–120° is capable of ensuring the best results.

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Keywords: Ingot forging; V-shaped die; FEM simulation; Porous plasticity; Ductile damage

1. Introduction

Large metallic components like shafts, utilized for power plant turbines or ship propulsion, are manufactured by ingot forging. An ingot is a large, cast block of steel. The casting process usually gives rise to an ingot containing a number of defects such as porosities due to improper feeding or gas formation, segregations or coarse microstructure due to long cooling time. These defects can, to some extent, be cured by substantial hot forging after casting the ingot in order to ensure a sound, final product.

Ingot forging and die layout is mostly based on accumulated knowledge gained through practical experience. In general, it consists of an ingot being compressed hydraulically by a flat upper die against a V-shaped lower die (Fig. 1). After compression, the upper die is removed, and the ingot is lifted from the lower die and rotated along its centre axis. Thereafter it is again placed into the V-groove and compressed once again by the upper die. This is

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continued for a number of press strokes until the cross-section is sufficiently deformed. Then the ingot is displaced by axial feeding in-between the dies and a new cross-section is forged. By practical experience, Nasmyth (1850) noticed that forging using a V-shaped lower die improved the internal soundness of the forged ingot and estimated the optimum angle to be around 80° . Slipline field analysis available in Johnson (1992) provides theoretical insight into the deformation mechanics of the process and confirms the superiority of V-shaped lower die geometries against the flat lower die.

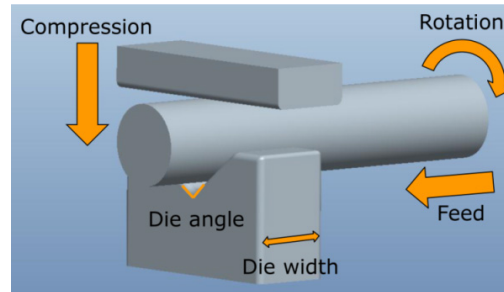


Fig. 1. Schematic representation of the ingot forging process.

The investigation on ingot forging is generally constrained by the technical impracticability of performing experiments in full-size ingots in a wide range of operating conditions due to the overall size, load requirements and cost of the ingots, which may be worth several hundred thousands of Euros. The alternative is to acquire fundamental knowledge of the process by means of small-scale experiments with model materials (Christiansen et al., 2014) and/or finite element analysis.

The aim and scope of this paper is to illustrate how the overall soundness of the ingot after forging can be quantified by means of finite element modelling using a porous plasticity model, where relative density $R = \rho/\rho_0$ is the measure of damage, or using a fully dense model with the uncoupled normalized Cockcroft & Latham criterion, where the integral of the ratio $\sigma_1/\bar{\sigma}$ of the principal stress to the effective stress throughout deformation is the measure of accumulated damage. Examples of the two damage measures and their distributions in the ingot after forging are presented and discussed. Effective plastic strain is also used as a quality measure of the forging process because large plastic strains are required to ensure recrystallization of the cast steel microstructure. The optimum angle of the V-shaped lower dies is estimated using a combination of damage and effective strain measures.

2. Finite element formulation

The finite element formulation utilized for fully dense materials is the so-called quasi-static flow formulation, which is based on the following variational statement:

$$\int_V \bar{\sigma} \delta \dot{\epsilon} dV + K \int_V \dot{\epsilon}_{ii} \delta \dot{\epsilon}_{jj} dV = \int_S t_i \delta u_i dS \quad , \quad (1)$$

where V is the volume of the ingot limited by the surface S . S_u and S_f are parts of the surface, where velocities and tractions are prescribed, $\bar{\sigma}$ is the effective stress, $\dot{\epsilon} = \sqrt{2/3 \dot{\epsilon}_{ij} \dot{\epsilon}_{ij}}$ is the effective plastic strain rate, K is a large constant penalizing the volumetric plastic strain rate $\dot{\epsilon}_{ii}$, t_i are the surface tractions and u_i are the velocities. The extension of the flow formulation to porous plasticity is based on the following variational statement:

$$\int_V \sigma_f \delta \dot{\epsilon}_R dV = \int_S t_i \delta u_i dS \quad , \quad (2)$$

where σ_f is the apparent flow stress of the porous material and $\dot{\varepsilon}_R$ is the effective strain of the porous material. Further details on the theoretical and computational aspects of the finite element flow formulation and of its extension to porous plasticity can be found in Nielsen et al. (2013) and Oh et al. (1987).

3. Numerical simulation layout

The finite element commercial software Deform is utilized for the numerical simulations of the ingot forging process. The ingot is considered to be 2000mm in diameter and the dies to have a width of 1000mm. These dimensions were taken from industrial practise (Christiansen et al., 2013). Due to the ratio of the die width to the ingot diameter of 1000mm/2000mm = 1/2, plane stress is assumed in the simulations. The ingot is made from a 42CrMo4 steel, commonly used for shafts, with flow stress data being dependent on strain, strain rate and temperature. The flow stress data was taken from Deform's database and copes with the experimental findings presented in Spittel et al. (2009). The ingot is modelled using 2067 linear quadrilateral elements. The dies are modelled as rigid-contact elements. The forging procedure consists of 17 compressions with intermediate rotations of 45°. Each compression is done moving the upper die 200 mm downwards. This procedure is rather similar to industrial practise. Fig. 2 shows an example of the finite element meshes at the beginning and end of the numerical simulation.

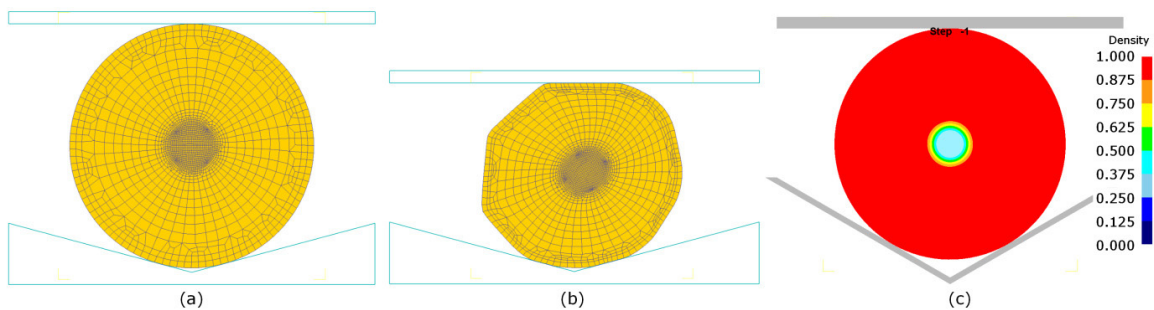


Fig. 2. Initial (a) and final (b) finite element meshes. (c) Distribution of the initial relative density for the finite element simulations based on porous plasticity.

Two different series of simulations were performed. In both series, different lower die angles of 60°, 90°, 120°, 150° or 180° were utilized for forging one cross-section according to the forging plan. The evolution of damage during forging was then quantified either by the relative density R for the porous formulation, or by the uncoupled, normalized Cockcroft & Latham ductile damage criterion (Oh et al. 1979):

$$D = \int \frac{\sigma_1}{\bar{\sigma}} d\bar{\varepsilon} \quad , \quad (3)$$

where D is the accumulated damage, σ_1 is the largest principal stress and $d\bar{\varepsilon}$ is the effective plastic strain increment. Damage is only accumulated if $\sigma_1 > 0$.

In order to replicate a typical casting defect along the centre line of the ingot the centre region of the ingot is assumed to have a relative density $R=0.25$ up within a radius of 100mm, followed by an annular region of 200mm radius, where R increases linearly up to 0.9. The remaining geometry of the ingot is assumed to be fully dense. This density profile is shown in Fig. 2(c).

4. Results and discussion

4.1. Simulation based on Cockcroft & Latham's ductile damage criterion

Fig. 3 shows the numerical prediction of the accumulated ductile damage after forging with two different geometries of the lower die.

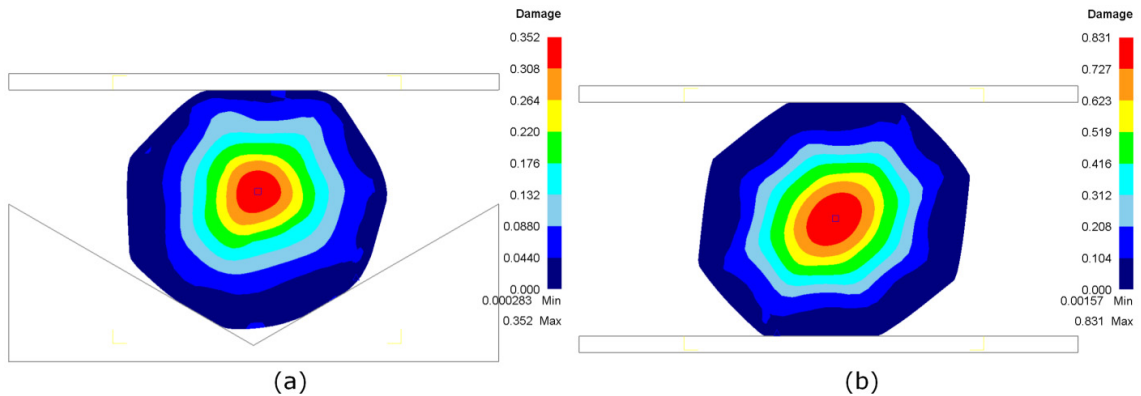


Fig. 3. Accumulated ductile damage when forging with V-shaped lower dies with (a) 120° and (b) 180°.

As seen, substantially less accumulated damage is predicted when applying a V-shaped lower die with 120° as compared to that resulting from a flat lower die (180° angle). The distribution of effective plastic strain is shown in Fig. 4. and allows concluding that forging with a flat lower die provides substantially larger values of plastic strain than those attained in a V-shaped lower die with 120°. This result creates a difficulty in evaluating which lower die is the 'best' because the flat die is simultaneously responsible for imposing the largest ductile damage and the largest plastic straining, which promotes the formation of sound microstructures. In contrast, the V-shaped lower die with 120° provides less accumulated damage but also less plastic straining.

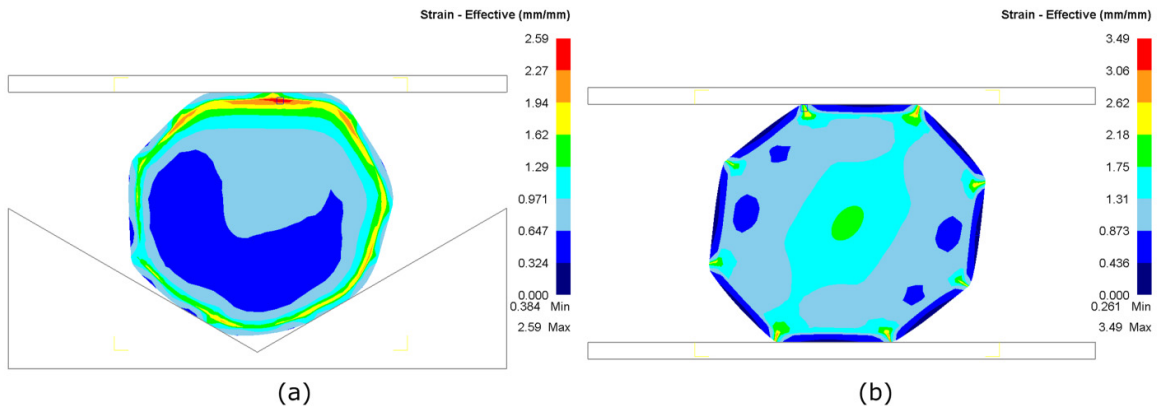


Fig. 4. Effective plastic strain when forging with V-shaped lower dies with (a) 120° and (b) 180°.

4.2. Simulation based on porous plasticity using relative density as a damage criterion

Fig. 5 shows the numerical prediction of relative density after forging with two different geometries of the lower die.

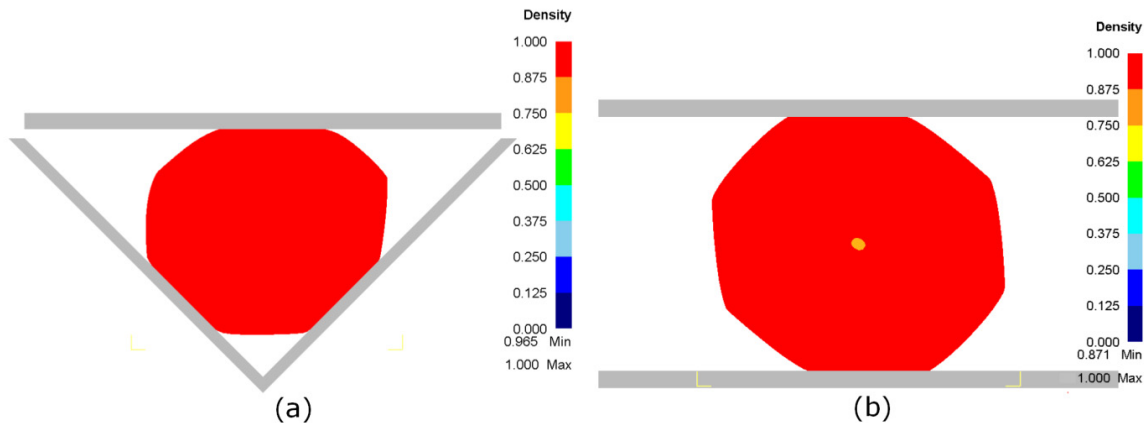


Fig. 5. Relative density when forging with a V-shaped lower die with (a) 90° and (b) 180°.

As seen in Fig. 5, the V-shaped lower die with 90° is capable of ensuring full densification of the ingot whereas the flat lower die (180°) leaves a low density region with $R=0.9$ at the centre of the ingot. The predicted distribution of effective strain is included in Fig. 6 and allows concluding that the two distributions are more similar than those included in Fig. 4.

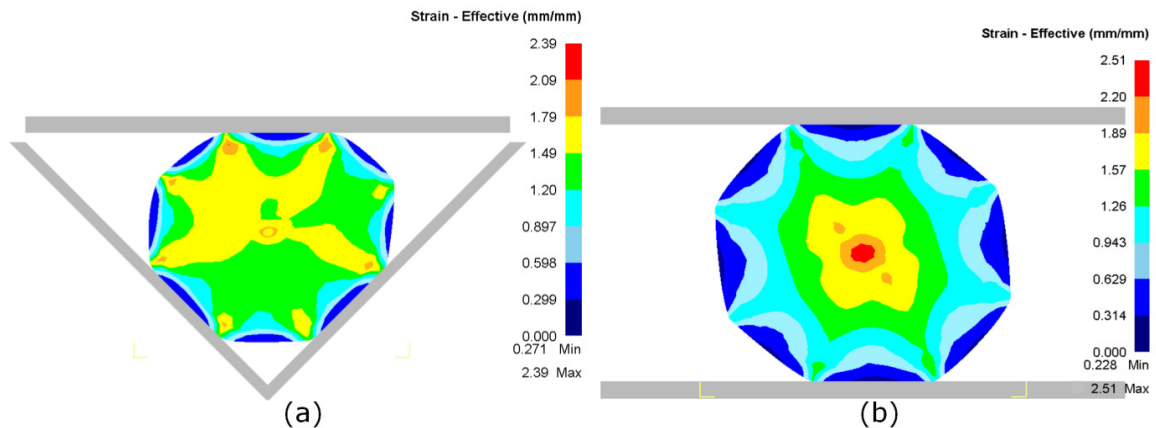


Fig. 6. Effective plastic strain when forging with a V-shaped lower die with (a) 90° and (b) 180°.

4.3. Quantitative evaluation of the optimum angle of the V-shaped lower die

The optimum angle of the V-shaped lower die is quantitatively evaluated by combining the distribution of effective plastic strain and ductile damage resulting from finite element analysis. Larger values of the effective plastic strain are preferred for microstructure purposes. Thus, its contribution to the quantitative evaluation of the optimum die angle was built upon the largest minimum plastic strain occurring in an element and the largest average effective strain occurring in all the elements.

Smaller values of ductile damage are preferred to avoid the growth of voids. In case of the uncoupled finite element simulations, the optimum die angle was determined as the one giving smallest accumulated damage in the most critical element and smallest average accumulated damage of all elements. In case of the coupled finite element simulations based on porous plasticity, quantitative evaluation of optimum tool geometry is based on the largest relative density in the most critical element and the largest average density of all elements.

In each category, the best lower die angle is assigned with the value '1' and the other die angles are assigned values ranging from '0' to '1' according to their relative performance to the best die. Hence a maximum of 4 points is possible if one lower die angle is best in all the different evaluation criteria. The final score is normalized by 4 to obtain the average ranking for each lower die angle regarding each evaluation criterion. The scores for the different lower die angles can be seen in Fig. 7.

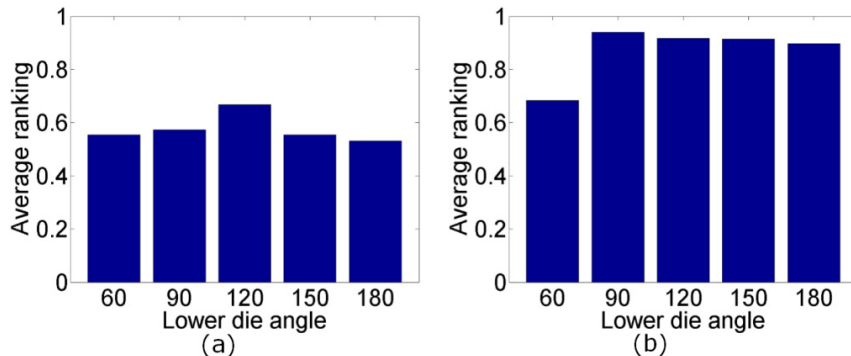


Fig. 7. Optimization of the angle of V-shaped lower die. (a) employs uncoupled ductile damage whereas (b) makes use of coupled ductile damage based on porous plasticity.

As seen in Fig. 7, there are marked differences regarding the optimum angle of the V-shaped lower die angle. When applying the uncoupled ductile damage approach, the best performance is obtained at 120° and this result is somehow distinct from the others. When applying the coupled approach based on porous plasticity the best performance is obtained at 90°, but the results for larger angles are very close and do not show a clear advantage of the optimum value compared to the others.

5. Conclusion

Finite element analysis was utilized to optimize the angle of the V-shaped lower dies in ingot forging. Both uncoupled ductile damage and coupled ductile damage based on porous plasticity models were employed. Results show that both approaches predict an optimum angle of the V-shaped lower die angle in reasonable agreement with what is currently used in the forging industry.

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